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Faculteit Bedrijfseconomische Wetenschappen

master handelsingenieur

Masterthesis

A literature Review on Planning Models for Synchromodal Transportation

Nohaila Sabi

Scriptie ingediend tot het behalen van de graad van master handelsingenieur, afstudeerrichting operationeel management en logistiek

PROMOTOR :
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A Literature Review on Planning Models for Synchromodal Transportation

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The increased container throughput at the ports and the changing transportation market, due to, for example, the COVID-19 crisis, demand a new way of working in the transportation industry. The need for a sustainable transportation market with less societal impact, e.g., congestion and noise, was never this high. Researchers and governments stress the importance of synchromodal transportation. Synchromodality will enhance the transportation industry's economic, societal, and environmental effects. Although synchromodality receives much attention from important authorities like the European Commission, its implementation by companies seems far away. This master thesis reviews the current synchromodal planning models, to find the trends and gaps in the scientific literature. This thesis illustrates that it is not a coincidence that implementation is still a far-away concept. The synchromodal planning models are rather theoretical games than ready-to-implement models.

Keywords: synchromodality, planning models, operational level, literature review

1. Introduction

On the 31st of October 2021, 30,000 people gathered in Glasgow for the climate conference. Politicians and company leaders sat together to set goals with the objective to minimize climate change (De Standaard, 2021). The transportation industry is an important sector to be discussed. According to the American Environmental Protection Agency (EPA), transportation is the most polluting sector. In 2019, the American transportation industry contributed 29% to the total greenhouse gas emission (EPA, 2021). Concerns about the transportation industry are also present in Europe. The demand for freight transport will triple by 2050, causing greenhouse gas emissions to double (Punte, 2019). It is important to start making sustainable decisions that will fulfill the needs of the customers without threatening the environment.

ALICE is a European technology platform that facilitates research and implementation of innovative logistics and supply chains in Europe. The European Commission aims to achieve an emission-free Europe by 2050. This objective requires research on different concepts in logistics and supply chains (Punte, 2019). For example, how can we meet the rising demand for transportation while decreasing the external effects on the environment? To achieve an emission-free Europe, ALICE has the ambition to implement the physical internet before 2030. The physical internet is a relatively new concept for freight transportation (Section 2 provides a definition). ALICE composed a roadmap to illustrate its goals and the way towards them. The end goal is the physical internet, yet the roadmap shows other preliminary concepts like intermodal and synchromodal transportation (Punte, 2019).

During the corona crisis, which started in Europe in March 2020 and is still ongoing, the transport industry changed. Firstly, the lockdowns increased the demand for freight transport. People prevented themselves from getting infected by avoiding going to stores to buy the goods they needed. As a result, they ordered online. Also, restaurants and non-essential stores which had to close during the lockdown offered their goods online. Secondly, the demand for freight transport became more volatile. Company closures made it challenging to forecast the demand for freight transport, and the lockdown of entire countries reduced accessibility to zero. Higher demand for freight transport harms the environment. The unpredictable demand and unanticipated disturbances have shown that a new way of working is needed. Synchromodality can be this new way of working. Synchromodal transportation results in a more sustainable solution and offers flexibility (Delbart et al., 2021), tackling both problems, i.e., the higher and more volatile demand. To implement synchromodality, research about the planning models is required.

This literature review categorizes the scientific work in this research field over the past decade. The aim is to detect trends and gaps in the literature. More specifically, this research wants to answer the question if the current synchromodal planning models are ready to implement. It is organized as follows. Section 2 discusses the concepts and terminology and compares the different concepts relevant in the transportation field. Section 3 provides the methodology used to accomplish this literature review. In Sections 4 to 7, the different models are reviewed. The main characteristics to evaluate the models are the planning level, the type of model implemented, the objective function, and the type of data applied to assess the model. Finally, Section 8 gives the conclusion of this paper.

2. Concepts and Terminology

This section provides a definition of different concepts that are relevant to this paper. *Intermodal transportation* is the oldest concept of the three concepts which will be discussed in this section. Intermodal transportation is the use of different modes of transportation during one route from origin to destination (Crainic, 2007). In particular, the change of the mode of transportation does not require loading and unloading single goods from one mode to another. The goods are stored and transported in containers. Hence, containerization is an important element of intermodal transportation. The qualities of every mode can be utilized in an intermodal network, contributing to better economic performance, and minimizing external costs of transportation (Mathisen, 2014). Currently, intermodal transportation is implemented by various companies. The Belgian company Move Intermodal has made use of a European intermodal network for over 30 years now. Since 1984 LKW Walter executes their transport on an intermodal way. Both companies stress on their websites the benefits of sustainability, efficiency, flexibility, and cost minimization (MoveIntermodal, LKW Walter).

The physical internet is, contrary to intermodal transportation, a relatively new concept that appeared in literature for the first time around 2011 (Pan, 2017). There are a variety of definitions; moreover, since it is a relatively new and innovative concept, the definition is still vague. The term is a metaphor for the digital internet. Analogous to the digital internet that transports data, goods are transported through transportation networks, using standardized protocols. In the digital internet, a sender is not concerned about the route a mail is taking, or if the message is sent in different parts, but only about the correct arrival of the mail at the destination; the same is supposed to be achieved in the physical internet (Ambra, 2019). Goods are transferred in universal π-containers: these are reusable, modular, and smart containers that have different sizes and can be composed as shown in Figure 1 (Pach et al., 2014). Furthermore, there is horizontal collaboration between different agents in the supply chain (Sternberg and Norrman, 2017). Horizontal collaboration in logistics is defined as the cooperative behaviour of parties at the same level of the supply chain, e.g., the collaboration between different logistic service providers. Hence, horizontal collaboration is the collaboration between competitors. On the other hand, the physical internet, analogous to intermodality, also applies vertical integration. Vertical integration is the collaboration of different parties at different levels of the supply chain, e.g., a supplier and a producer that share stock information to synchronize delivery days (Basso et al., 2018). The implementation of a physical internet network results in increased efficiency and a more sustainable use of transportation (Sternberg and Norrman, 2017).

Synchromodality is defined by Verweij (2011) as the ability to shift between different transport modes while the goods are in transit, based on real-time data, in view of optimizing the service level and/or minimizing the costs. Behdani et al. (2016) and Tavasszy et al. (2015) describe synchromodal transportation as the horizontal integration of freight transport planning while using different means during the route. Acero et al. (2021) give an encompassing description, i.e., synchromodality is a planning system for multimodal transport whereby different agents of the supply chain are involved. Those agents work together in an integrated and flexible way, which is why they can interact quickly within a dynamic environment (Acero, 2021).

Table 1 shows the similarities and differences between intermodality, synchromodality, and the physical internet.

Figure 1. Composable π-containers (Tran-Dang & Kim, 2018).

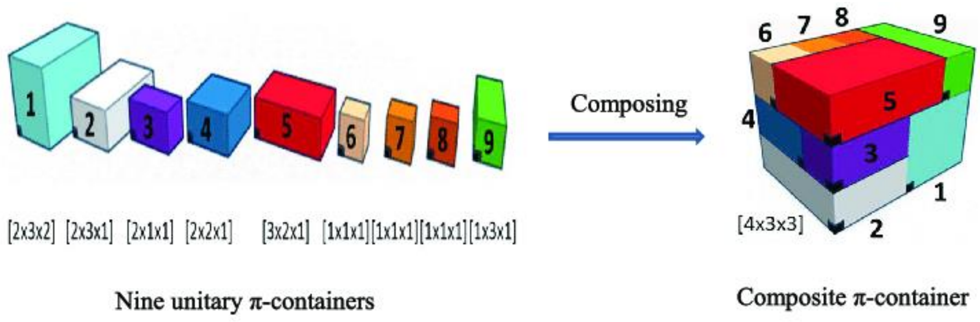


Table 1. Comparison of the relevant aspects related to intermodality, synchromodality, and the physical internet.

	Intermodality	Synchromodality	Physical Internet
Multimodal	x	x	x
Fixed route	x		
Vertical integration	x	x	x
Horizontal integration		x	x
Containerization	x	x	x
Modular containers			x

3. Methodology

The methodology used is the systemic literature review presented by Durach, Kembro, and Wieland (2017). The guidelines are defined in six steps, which are shown in Table 2 (Durach, 2017).

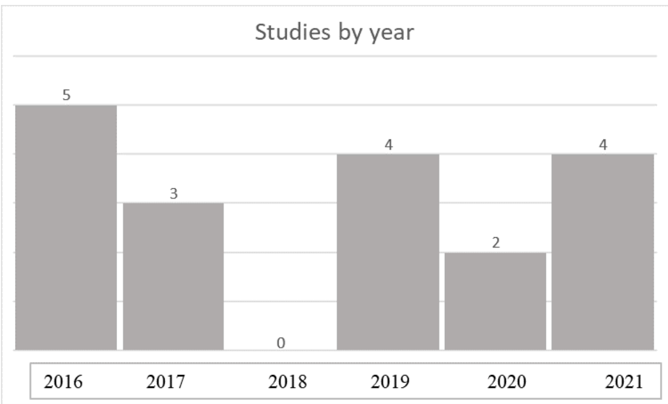
Table 2. Six steps in a systematic literature review.

1. Research question
2. Required characteristics
3. Baseline sample
4. Synthesis sample
5. Synthesize literature
6. Report results

The research questions have been discussed in the introduction. Only English and Dutch sources have been considered for this paper; the electronic databases used are primarily Web of Science, Google Scholar, and ResearchGate, complemented by the ancestry approach. There is no time restriction. Yet, synchromodality is a relatively new concept which means that the papers on synchromodal planning models are recent. A quick search on the Web of Science with the search term 'synchromodal transportation planning model' showed 15 papers, of which the oldest dates from 2014. Figure 2 shows the articles per year, reviewed in this paper. Other keywords used were 'synchromodal planning models', 'synchromodality planning models', and 'synchromodal model'.

Initially, only papers published in journals with an impact factor in the first two quartiles were considered; however, sources with a lower impact factor are included in this research if these sources are mentioned in the papers with a high impact factor. Reading the abstract and conclusion gives clarity about the relevance of the paper.

Figure 2. Number of studies per year for synchromodal transport planning models.



4. Planning levels

In the literature, planning models are classified based on the planning level. The planning level is either strategic, tactical, or operational (Delbart et al., 2021). At each level, different time horizons and decisions are taken into account. This section gives an overview of the actions taken at the different levels.

4.1. Strategic level

At the strategic level, the design of the physical network takes place. It is also essential to specify the infrastructure and make investment decisions (Delbart et al., 2021). A market analysis makes it easier to determine the nodes and their connections. Required data about transportation demand, the number of flows between the origin and destination, and the shipment size is acquired at this phase. Before making investments in infrastructure, it is necessary to examine the current infrastructure and the means available (Behdani et al., 2016). The time horizon for the strategic level is around three to five years.

Hence, an effective synchromodal network is designed at the strategic level (Behdani et al., 2016).

4.2. Tactical level

The time horizon of tactical decisions is around a year. The tactical level involves the service design (Delbart et al., 2021), which means that the routes within the network are defined together with the timing and the schedule of the modalities (Tavasszy et al., 2017). Here, orders are not assigned to a specific route. The goal is to illustrate the network's capability; what are the possible paths in this network. Furthermore, the frequency and capacity over each corridor should be determined for the different modalities (Behdani et al., 2016). Besides that, the terminal operations, e.g., the possibility to store goods or consolidate orders at a specific terminal, are specified at this level. Data about the predicted freight volume is required to design the service (Qu et al., 2019).

4.3. Operational level

The operational level operates on a daily basis. In contrast to the strategic and tactical levels, operational choices are made in a detailed environment, where information at the container level is available (Delbart et al., 2021). Operational problems are routing problems and assigning freight to a particular transport service (Behdani et al., 2016). The routing decisions are taken locally and in the near future, contrary to the tactical level (Qu et al., 2019). Synchromodal transport focuses on flexibility and the ability to perform in a dynamic environment. Accordingly, real-time adjustments are also realized at this level (Delbart et al., 2021). The decision-maker can be a human actor or a digital platform (Tavasszy et al., 2017). However, a combination of the two is more realistic.

The analyses performed at the strategic and tactical level in a synchromodal transport network are approximately similar to the studies conducted in an intermodal network (Behdani et al., 2016). The novel part of synchromodality is the addition of real-time adjustments or route planning at the last minute. Consequently, this literature review concentrates on planning models at the operational level.

5. Methodology

This section provides a categorization of the different planning models based on the methodology used by the researchers. Table 3 shows the reviewed planning models and the methodology applied in each model.

Table 3. Synchromodal planning models.

Author (year)	Problem tackled	Model
Behdani et al. (2016)	Optimal modal choice & Synchronization of departure times	Mathematical model
Mes and Iacob (2016)	Routing problem	multi-objective k-shortest path
Zhang and Pel (2016)	Routing problem	Mathematical model (SynchroMO)
Van Riesen et al. (2016)	Routing problem	Decision Tree
Pérez Rivera and Mes (2016)	Consolidation of freight	Markov model
Agbo and Zhang (2017)	Modal choice at a hinterland network	MILP
Pérez Rivera and Mes (2017a)	Consolidation of freight	Markov model
Pérez Rivera and Mes (2017b)	Scheduling drayage operations	MILP
Ambra et al. (2019)	Routing problem	Simulation approach
Qu et al. (2019)	Re-planning in case of a delay	MILP
Resat and Turkay (2019)	Routing problem	Multi-objective MILP
Pérez Rivera and Mes (2019)	Combining drayage operation with long-haul transport	Markov model + MILP
De Koning et al. (2020)	Container assignment to trucks and barges	Simulation approach
Larsen et al. (2020)	Synchronizing barge departures	Departure Learning
Yee et al. (2021)	Modal choice for single shipment	Markov model
Larsen et al. (2021a)	Simultanous planning of containers and truck routes	MILP
Larsen et al. (2021b)	Synchronizing barge departures	Secure Departure Learning
Zhang et al. (2021)	Routing problem	Mathematical model

5.1. Markov decision model

Pérez Rivera and Mes (2016), Pérez Rivera and Mes (2017a), Pérez Rivera and Mes (2019), and Yee et al. (2021) apply a Markov Decision Process (MDP) to deal with the uncertainty in a synchromodal network.

A Markov Decision Process is a mathematical model that facilitates making decisions in a dynamic environment over time. The main goal is to minimize the total cost. This cost includes the price of changing from the current state to another state (for example, switching to a faster mode of transportation at a terminal to meet the customer's demand entails costs for unloading and loading the containers) and a penalty cost. This penalty is charged when the continuation in the current state results in not meeting the initial goals, e.g., if an order is transported by train like initially planned and the decision-makers choose to not deviate from the original plan, a penalty cost is taken into account when the order arrives late at the customer (Bellman, 1957). The MDP examines the performance over time. The performance is partly under the decision maker's control, and partly random (Pérez Rivera & Mes, 2017a).

Pérez Rivera and Mes (2016) deal with the consolidation of freight, i.e., assigning orders to the various modes and combining orders, in long-haul round trips. The researchers integrate information about the future through a simulation of future demand. Every node in the network can be an origin or a destination node, depending on the shipment. The arrival of the demand is stochastic, which means it is not known precisely, but the probability distribution of the demand is known. The objective function is to minimize the total cost. In the paper, two modalities are mentioned, namely barge and road transport. Approximate Dynamic Programming is implemented to discover the optimal set of solutions. Approximate Dynamic Programming is an algorithm that solves large and complex problems that are primarily stochastic. Solving a problem with Approximate Dynamic Programming means that from an initial state, certain decisions are evaluated by determining the consecutive state caused by that decision. The algorithm restarts once the successive state is defined (Powell, 2009).

Pérez Rivera and Mes (2017a) study the same research question discussed in the previous paragraph. However, they attempt to improve the heuristic method they implemented by combining Approximate Dynamic Programming with another heuristic. Approximate Dynamic Programming can sometimes lead to a local optimum. This extra heuristic tries to improve imperfect approximations of the solution (Pérez Rivera & Mes, 2017a).

The most recent article by Pérez Rivera and Mes (2019) addresses a scheduling problem that combines long-haul transport with drayage operations. They consider an extensive network of drayage operations and long-haul operations and aim to minimize the total cost of the network. The drayage operations consist of the short movements of the containers around the port or terminals, while long-haul operations are the long-distance routes between far away terminals. Drayage operations are divided into end-haulage and pre-haulage jobs. Pre-haulage jobs are the movements of goods between the initial starting point and an intermodal terminal, and end-haulage jobs are the routes between an intermodal terminal and the customer. The paper integrated the scheduling of drayage operations with long-haul transport by simulation. The researchers used different methods to model the different operations. Pérez Rivera and Mes's (2017a) model is applied to design long-haul operations. To implement the drayage operations into their model, they used a mixed-integer linear programming problem discussed in Pérez Rivera & Mes, (2017b). The mixed-integer linear programming problem implemented is explained in section 5.2.1. Besides the different modelling methods, the decisions taken for the different operations also differ. Drayage operations are all executed by trucks. Here it is essential to assign the right truck at the right time to the correct order. For long-haul operations, decisions about the modal choice are vital.

In Yee et al. (2021), the main goal is to reduce cost by deciding on the optimal modal choice for a single shipment. Stochastic travel times based on real-time data are applied to find the optimal solution. The stochasticity in the travel times is modelled using different scenarios, each with a specific probability of occurrence. As stated previously, the objective function minimizes the total transport cost. This cost includes the transportation cost, the transshipment cost, the storage cost, and the penalty cost for late delivery. The modalities included in their research are road transport, rail transport, and inland waterways. The model incorporates the capacity constraints for the different modalities. Traceability, the ability to track shipments in transit, is an essential component of the model since the adjustments are made based on real-time information about travel times. To find the optimal modal choice for the shipment, backtracking is executed. This solution algorithm starts at the current state and first analyses the effect of each action until the final state. Afterward, backtracking is used to evaluate the preceding conditions and determine the optimal choice.

Yee et al.'s (2021) model is most related to the model of Pérez Rivera and Mes (2017a). The main difference is the source of uncertainty. Yee et al. (2021) consider travel times as stochastic, while Pérez Rivera and Mes (2017a) consider the arrival of orders as stochastic. Besides that, Yee et al. (2021) look at the single shipment level, making the solution method for the MDP easier. In contrast, Pérez Rivera and Mes' (2017a) goal is to consolidate orders.

5.2. Mathematical models

5.2.1. Mixed-integer linear programing

The most often used methodology to solve optimization problems in a synchromodal network is mixed-integer linear programming (MILP).

In Pérez Rivera and Mes (2017b), MILP is used to determine the scheduling of drayage operations. Pérez Rivera and Mes (2017b) describe drayage operations as the delivery and pick-up of empty or loaded containers from and to an intermodal terminal where long-haul modes arrive and depart. All drayage operations are carried out by road transport. The original scheduling plan modifies if necessary. A delay or new requests for pre-haulage or end-haulage operations can cause the shift to a new plan. The Logistic Service Provider decides whether and which container will be assigned to each customer in view of minimizing the total cost. This cost includes the routing cost and the terminal assignment cost. Heuristics are used to solve the MILP problem. First, a static matheuristic, a hybridization between a metaheuristic and exact procedures (Kramer et al., 2015), narrows the feasible space by adding constraints to the MILP. For example, eliminating arcs for which the travel time is larger than the two smallest travel times connecting the nodes. Then, a dynamic matheuristic builds further on the static matheuristic to solve a replanning problem when new orders arrive or in case of a delay. Hence, the difference between the two matheuristics is that the static matheuristic finds an optimal solution when given all the information at hand at that time. In contrast, the dynamic matheuristic re-optimizes the optimal solution found by the static matheuristic because a disturbance occurred, or a new order has been placed.

Agbo and Zhang (2017) contribute to the literature with a MILP model that chooses the optimal modal choice for freight transport at a hinterland network. The integrated planning of the three transport modes and the terminal services is the synchromodal aspect of their study. The departure of inland waterways transportation and trains is not predetermined, yet it is based on the demand and the situation at a particular time. Barge, road, and rail transport are deployed to move the freight from origin to destination. The number of departures of barges and trains is limited, while road transport capacity is considered infinite. There is only one origin and destination, with intermediate terminals. Early or late arrivals at the destination are penalized. The objective is to minimize the total operational cost. CPLEX 12.0, a commercial software program, was used to find the optimal solution for this optimization problem.

In Qu et al. (2019), a re-planning model is proposed by using MILP. The network consists of multiple origin nodes and destination nodes. The nodes can be connected by three different modalities, i.e., ships, trains, and trucks. In the case of early arrival, storage costs are considered. Meanwhile, delays cause a penalty cost. A delay at any node aside from the destination node triggers a re-planning of the current state. The model tries to anticipate the delay by using a faster transport mode, or by traveling to another node. New shipments are not allowed after the initial scheduling plan; hence, re-planning based on new orders is not in the scope of this research. CPLEX 12.0 is used to solve the MILP. The objective of this model is to minimize the total operational cost.

Resat and Turkay (2019) established a multi-objective mixed-integer linear programming model to design routes for orders in a synchromodal network, which they solved in CPLEX 12.1. They initially modelled a non-linear programming problem, yet it is complex and time-consuming to compute a solution to such a non-linear model. Hence, they simplified the model by adding relaxations. The initial model was non-linear as a result of various reasons, e.g., the objective function of CO_2 emissions, or the multiplication of two variables for computing the transportation time. The main objective is the minimization of the total transportation cost, yet the minimization of the travel duration and the minimization of CO_2 emission are simultaneously considered as objective functions. The model looks for the Pareto optimal solutions, meaning those solutions where none of the objectives can be improved without hurting another objective (Engau & Sigler, 2020). The modalities incorporated in the model are barge, rail, and road transport. Early and late arrivals are penalized.

Larsen et al. (2021a) simultaneously plan container routes, container modalities, and truck routes in their model. This integrated view makes it possible to decide about the loading and unloading of the trucks as well. Trucks, trains, and ships are used to move the containers in the network. They describe the model as a MILP problem, intending to minimize the costs. The costs taken into account are storing containers, loading and unloading of vehicles, slots on scheduled services, movements of trucks, and parking costs. A controller solves this minimization problem. Larsen et al. (2021a) do not specify the controller, yet they assume that the controller is a large transportation company with well-integrated departments. Another essential factor is that the company has enough orders to have a qualitative demand forecast. They also do not specify in the paper if this model is resolved by a human controller, an ICT platform, or a combination of both. The controller is provided with accurate, real-time data about the synchromodal network and the forecasted demand. At each time, the controller chooses the sequence of decisions that will optimize the cost function.

5.2.2. Other mathematical models

Behdani et al. (2016) contribute to the literature by introducing a mathematical model that determines the optimal modal choice and synchronizes the departure times of the different modalities. The modalities taken into account are rail, road, and inland waterway transport. The objective is to minimize the total cost. Adding penalties for early and late arrivals, and optimization of travel times is also included in the objective function. Re-planning is not possible in the model. The synchromodal part of this model is the synchronization of the departures of barge and rail transport. In the first step, the barge schedule is optimized, followed by optimization of the rail schedule, given the barge schedule. However, a capacity constraint for the number of departures for rail and barge transport is implemented in the model. In contrast, trucks have no capacity constraint w.r.t. departures.

Zhang and Pel (2016) present the SynchroMO model. SynchroMO stands for synchromodal modelling operator. A mathematical model chooses the optimal route by minimizing the total costs. Planning software is used to compute this optimal result, i.e., TransCAD. The containers can be assigned to road, rail, and inland waterway transport. Orders are released the day they have to be executed, resulting in a sort of real-time environment; routes are planned at the very last time to use the new acquired information to handle the dynamic environment.

Zhang et al. (2021) illustrate a multi-objective optimization problem. The objectives are minimization of transportation costs, travel times, and emissions of CO_2. In the paper, they solve a mathematical problem using a heuristic approach. The reason for choosing a heuristic is the long computation time for an exact solution. An adaptive large neighborhood search is introduced to solve the multi-objective optimization problem by adding and removing nodes for a specific shipment and comparing the result with the previous route to find out if there are any enhancements. The objectives differ among carriers. This model is able to deal with the divergent preferences of the decision-maker. Preferences are added to the model as a minimum and maximum value for the result of the objectives: the set of feasible solutions is found by optimizing the three objectives, however preferences are added to choose the solution that is the closest to the wishes of the decision-maker (e.g., a planner may prefer the objective of cost minimization only if the CO_2 emissions and the travel times are between an under and upper limit).

5.3. Learning models

Larsen et al. (2021b) propose Secure Departure Learning to align barge departures with the demand of multiple truck operators. Section 4 gives an overview of the decisions taken at different planning levels. Schedules of departures are generally considered at the tactical level. Yet, in this paper, the departure times are not fixed; the times differ based on real-time information about the demand for barge transport by the truck operators and the operational cost. The model takes into account one barge operator and different truck operators. The objective is to minimize the total operational costs of all parties involved. The barge operator aims to transport full ships, while truck operators target a cheaper alternative, i.e. the barge transport, moving their freights from origin to destination. Because the different operators are not open to sharing information about their costs, customers, planning method, etc., Secure

Departure Learning is introduced. Truck operators receive various possible schedules of the barge operator. Afterward, the barge operator receives in return for all the possible schedules the operational cost of the barge operators. The barge operator and the truck operators can co-plan their departures without sharing delicate information. The Paillier encryption method ensures the privacy of the information.

Previously, Larsen et al. (2020) introduced departure learning to route containers, barges, and trucks optimally. In the provided model, one barge and one truck operator co-plan the freight in the provided model without sharing sensitive information. Especially the truck operator hesitates to share information about its customers, costs etc., while the barge operator seeks to maintain its autonomy when scheduling the departures. First, the barge operator proposes to the truck operator some possible departures. The departures are found by minimizing the cost of the barge operator. Learning techniques are applied to facilitate choosing near-optimal departures in the future. Afterward, the truck operator solves the minimization problem of costs by scheduling the containers and trucks simultaneously, using the different barge departures. Because the operators share the profit, they both try to find the cheapest solution for both parties. To reflect that it is an integrated optimization problem, instead of a sequential one, the cost minimization problem of the truck operator contains the extra cost per container for the barge operator.

5.4. Heuristics and Simulation approach

De Koning et al. (2020) present a simulation approach for container assignment to trucks and barges under uncertainty. The uncertainty is caused by two elements, i.e., the arrival of the orders from the customers and the time slots requested at the port terminals. The terminals at the port are mostly controlled by other agents. Hence, the requested time slot of the terminals can differ from the actual time slot. De Koning et al. (2020) propose an online optimization problem. The suggested method divides the total planning period into multiple smaller periods, e.g., every period is 3 hours. In each time period, decisions are made based on the available data of the previous period. Taking decisions at different times makes re-planning possible. The algorithm provides different scenarios based on the probability of various uncertainties. To find the optimal route, where costs are minimized, an integer linear programming model is used for each scenario. However, the computing time is long. Hence, a heuristic approach would provide a reasonable solution estimate in less time. The paper does not specify a heuristic for this problem.

Ambra et al. (2019) describe a computational model to compose a route for an order. In the paper, they use simulation modelling to minimize the total cost of an order. The cost per km for the different transportation modes, i.e., barges, trucks, and trains, the storage costs, and the handling costs are taken into account. Re-routing is allowed in the model. Hence, the model considers a dynamic synchromodal network, where real-time information is simulated.

Van Riessen et al. (2016) use decision trees to assign freight to a specific route. It is debatable if their model contributes to the synchromodal planning literature due to the lack of real-time information and capabilities to re-plan the scheduled routes. However, the researchers discuss that their decision support system is established in a real-time environment since they apply a learning algorithm to the historical data. The learning algorithm keeps information about the historical optimal solutions together with information about the properties of the containers and orders. A mathematical model outlines the constraints and the objective function of the network. The objective is to minimize transportation costs for all containers. The decision tree is applied at container level. A human planner can apply this decision tree manually, or it can be automated. A human planner is capable of adding layers, due to the extra information and the experience over time, to the decision, which results in a better route. For example, the human planner is capable to prioritize one route over the other due to the information and experience the planner acquired over time. The modalities considered in the model are road, rail, and inland waterways.

In Mes and Iacob (2016), a multi-objective k-shortest path model provides a planner with a set of optimal routes that meet the criteria set. The planner's objectives are optimizing costs, travel time duration, and emissions. For this reason, the criteria set can be defined as the constraints of the multiple objectives, i.e., routes are only allowed or feasible if the travel duration is smaller than 3 days. The authors apply a heuristic to solve the k-shortest path problem, due to several challenges. A first challenge is that criteria and constraints are negotiable, which makes the objective coefficients unknown upfront. Another reason to apply a heuristic is that the human planner does not want one solution but wants to choose from a set of solutions. Hence, the planner can sort and filter out the optimal solution at a specific point in time for a specific order. The heuristic approach consists of two consecutive stages. First, the network is narrowed based on the origin and destination nodes; nodes the furthest away from the origin and destination are disregarded. This is called the offline stage. Afterward, a specific reduced network is chosen for an incoming order in the online stage, based on the characteristics of the order, e.g., capacity. Mes and Iacob (2016) use parameters to indicate the maximum increase in distance, travel time, and costs per route. These parameters constrain the model from computing every possible route, which would result in long computation times. Furthermore, the suggested model can serve as a re-planning algorithm by removing or adding nodes to the reduced network when real-time data is provided.

6. Objective function

Section 5 illustrates briefly the objective function that each model aims to optimize. However, the following section gives an overview of the different models and their goals. Table 4 summarizes these objective functions.

The three main goals of implementing synchromodality are reducing the environmental, societal, and economic impacts. However, most models only set one objective function, i.e., minimizing costs, and the models compute the effect of implementing synchromodality on the societal and environmental level.

Only three of the papers consider multiple objectives. Mes and Iacob (2016) optimize the total cost, CO2 emissions, and travel time duration. They implement the three goals by assigning a weight to each objective. The increase in the objective criteria of the following k-shortest path should be smaller than the assigned weights, e.g., the parameter for cost is 1.5, meaning that routes that increase the cost by more than 50% are not allowed.

Resat and Turkay (2019) have the same three objectives. However, the researchers prioritize the cost objective function. Their MILP has three objective functions.

Zhang et al. (2021) include the three different objectives, i.e., cost, travel time, and emission, in their model from the perspective of the various decision-makers. They state that decision-makers have other preferences, e.g., a client who wants the most sustainable route even if it is more expensive. The decision-maker's preferences are added to the model as minimum and maximum values.

Table 4. Objective functions of synchromodal planning models.

Author (year)	Single-objective	Multi-objective	Objective function(s)
Behdani et al. (2016)	x		Minimizing total cost
Mes and Iacob (2016)		x	Optimizing costs, CO2 emissions & travel duration
Zhang and Pel (2016)	x		Minimizing total cost
Van Riesen et al. (2016)	x		Minimizing total transportation cost
Pérez Rivera and Mes (2016)	x		Minimizing total cost
Agbo and Zhang (2017)	x		Minimizing total operational cost
Pérez Rivera and Mes (2017a)	x		Minimizing total cost
Pérez Rivera and Mes (2017b)	x		Minimizing total cost
Ambra et al. (2019)	x		Minimizing total cost of an order
Qu et al. (2019)	x		Minimizing total operational cost
Resat and Turkay (2019)		x	Optimizing costs, CO2 emissions & travel duration
Pérez Rivera and Mes (2019)	x		Minimizing total cost
De Koning et al. (2020)	x		Minimizing total cost
Larsen et al. (2020)	x		Minimizing total cost
Yee et al. (2021)	x		Minimizing total transport cost
Larsen et al. (2021a)	x		Minimizing total cost
Larsen et al. (2021b)	x		Minimizing total cost
Zhang et al. (2021)		x	Optimizing transportation costs, CO2 emissions & travel duration

7. Empirical studies

Most researchers substantiated their model by an empirical experiment. This section presents an overview of the different experiments and case studies applied. The empirical studies are compared based on the spatial characteristics of the network, data type, and results.

7.1. Spatial characteristics

7.1.1. Country

The majority of the case studies are applied to a region in Europe, specifically in the Netherlands. This is because the concept of synchromodality started in the Netherlands and received much attention from the European Union (Agbo & Zhang, 2017). Agbo and Zhang (2017) intentionally choose to implement their case study in a developing country, i.e., Ghana. Resat and Turkay (2019) prove their theory by implementing their model in the Marmara region in Turkey. These two papers are the only papers performing an experiment outside Europe.

However, to have a holistic view of synchromodality, it is essential to verify these models in different countries because spatial attributes differ. Trying out the models in different parts of the world is mainly important because a substantial ecological difference can be made if more countries apply synchromodality. Also, to raise awareness in different parts of the world, it is important that synchromodality retains the attention of researchers around the world. However, synchromodality stays an important concept especially in Europe for different reasons. Europe is a densely populated region; a lot of people live in a relatively small part of the world (Welch, 2017). All those people have needs that should be fulfilled. To satisfy their demand, a high capacity of supply is needed. This results in a high number of trucks serving people in a small region, which leads to congestion, pollution, accidents, and noise, necessitating a different solution. Synchromodality offers a better modal split which reduces the demand for trucks. Europe benefits from various inland waterways (Kelderman et al., 2016), which makes synchromodality possible.

7.1.2. Hinterland

In the literature, many planning models operate in a hinterland network. A hinterland is the area around a port where port activities take place (Notteboom & Rodrigue, 2007). Knowing that researchers discuss that intermodal transport is beneficial from around 400 kilometers (Mes & Iacob, 2016), studying synchromodality in a hinterland seems contradictory.

However, the interest in hinterland networks comes from the increasing throughput of containers at the ports, due to globalization and offshoring. A port can achieve a competitive advantage if its service level is more advanced than that of neighboring ports. The port should operate in a faster, more reliable system that cooperates with the dynamic environment to achieve this competitive advantage. Synchromodal transportation can be the solution to this problem (Behdani et al., 2016).

Besides the incentive of the port to create a competitive advantage, policymakers stress the importance of reducing the congestion around the ports (Agbo & Zhang, 2017). The limited road infrastructure and the increase in transport demand create congestion. The modal split results in fewer trucks on the road, which leads to a decrease in congestion (Behdani et al., 2016). Intermodality and synchromodality improve the modal split (Agbo & Zhang, 2017). However, intermodality lacks the flexibility that synchromodality offers (Ambra et al., 2019). This flexibility is needed in a hinterland environment, where disturbances and changes occur frequently. Hence, synchromodality offers a solution to both congestion and inflexibility.

7.2. Type of data

To establish the models, the papers apply empirical studies, either using real-life data or synthetic data (see Table 5).

For the majority of the studies, real-life historical data is used. E.g. , Agbo and Zhang (2017) applied historical port data of the port of Takoradi in Ghana. Another example is the paper by Ambra et al. (2019), who use the transportation data of a French retailer sending goods to multiple areas in France and Belgium. Most papers illustrate the corresponding model using an existing network, e.g., Yee et al (2021) clarify their model with a network that connects the port of Rotterdam with Milan with intermediate terminals. None of the studies conducted a real-life experiment; hence, so far, all studies can be considered as theoretical thought experiments.

Table 5. Data type used for the synchromodal planning model.

Author (year)	Real-life data	Synthetic data	Existing network
Behdani et al. (2016)	x		x
Mes and Iacob (2016)	x		x
Zhang and Pel (2016)	x		x
Van Riesen et al. (2016)		x	
Pérez Rivera and Mes (2016)		x	
Agbo and Zhang (2017)	x		x
Pérez Rivera and Mes (2017a)		x	
Pérez Rivera and Mes (2017b)		x	
Ambra et al. (2019)	x		x
Qu et al. (2019)	x		x
Resat and Turkay (2019)	x		x
Pérez Rivera and Mes (2019)		x	
De Koning et al. (2020)		x	x
Larsen et al. (2020)		x	x
Yee et al. (2021)	x		x
Larsen et al. (2021a)		x	
Larsen et al. (2021b)		x	x
Zhang et al. (2021)	x		x

7.3. Results

In this section, the results of the empirical aspects of the models are discussed. Some papers focus on the results of using synchromodality, such as the effect on costs and emissions. Other papers stress resulting differences of applying diverse models to the case.

7.3.1. No comparisons

Zhang et al. (2021) perform a case study to verify if their multi-objective model results in logical routes based on the prioritized objective. They applied 210 experiments. The experiments differ based on the weight intervals of the objectives. When costs are prioritized, barge transport is used more because it is the cheapest mode of transportation. However, in practice, barge transport is not utilized frequently due to the uncertainty accompanied by barge transportation. When time is the essential objective function, rail transport gets the more significant part of the demand due to the relatively higher speed of trains and the expensive road transport.

Resat and Turkay (2019) do not illustrate the benefits of implementing synchromodality and do not compare their model with other models. They just describe their theoretical application of the model in the Marmara region.

7.3.2. Comparisons between models and solving methods

Van Riesen et al. (2016) compare different online heuristics with their heuristic. They concluded that their heuristic outperformed the others when the demand had a specific pattern. When demand was considered stochastic, their heuristic also performed better, but the difference was not remarkable.

De Koning et al. (2020) also compare their method with other approaches, concluding that their simulation approach is more reliable.

Larsen et al. (2020) compare their suggested model with a benchmark model, considering road transport unlimited and always available while optimizing the containers separately. Their model plans the truck routes and containers simultaneously, resulting in an empty-to-full ratio of the vehicles lower than 3%. The researchers also stress that fewer trucks are needed in their model, which results in economic, social, and environmental benefits. Yet, the synchronized model results in more unsatisfied demand. Although unsatisfied demand is penalized, the model tries to limit empty rides of the trucks.

Pérez Rivera and Mes (2017b) compare their heuristic with a benchmark heuristic. They concluded that their heuristic obtained a better solution than the benchmark heuristic. In an earlier study (Pérez Rivera and Mes 2016), the researchers also compared the heuristic they used in the model, i.e., ADP, with a benchmark heuristic. The results show that ADP computes solutions that have significant cost savings compared to the benchmark heuristic.

Pérez Rivera and Mes (2017a) also compare the results of their ADP heuristic with a benchmark heuristic. Depending on the situation, one heuristic is better than the other, e.g., the benchmark heuristic is better if the model has short distributions of time-window lengths, yet ADP outperforms the benchmark heuristic in scenarios with longer time windows.

7.3.3. Comparisons between different concepts

Behdani et al. (2016) conclude in their illustrative case study that their synchromodal model has a cost reduction of around 20% compared to a system with a fixed schedule. This cost reduction results from fewer trucks and decreased penalty costs for waiting times at the origin. However, the cost difference between the suggested model of the researchers, where rail and barge departures are scheduled simultaneously, and a model, where rail departures are optimally scheduled after barge departures, is only 5%. The modal split of the synchromodal model is better though, positively influencing CO2 emissions and congestion.

Mes and Iacob (2016) discuss that for 39% of their orders, it is beneficial to shift from road to rail or inland waterway transport. The paper also states that synchromodality operates better for long distances than for short distances due to the better connections. Synchromodality results in a cost reduction of 10% and a decrease in CO2 emissions of 14,2%. These results are for single shipments without consolidation. Consolidation of orders results in a lower cost reduction, i.e., 3.9%; this is because consolidation opportunities come up when delivery windows have more wiggle room and unimodal road transport is faster than intermodal transport.

The study of Zhang and Pel (2016) revealed that synchromodality leads to a slight decrease in overall system costs. This decrease is the result of the modal shift resulting in fewer trucks. However, synchromodality causes extra handling because of the transshipments. On average, the handling movements increase by 40%. The rise in costs is lower than the decrease of costs due to the fewer trucks resulting in a net cost reduction. The delivery time of the goods shrinks from 22 hours to 15 hours; this supports the statement that synchromodality causes a modal shift without lowering the service level. Road transport decreases by 16%, which suggests that congestion decreases. However, the researchers question whether congestion wouldn't occur at the ports and terminals, when using synchromodality. Hence, it could only be a shift of the problem and not a solution. The environmental impacts reviewed in the paper show that the CO2 emission decreased by 28% thanks to the modal shift and the higher utilization rates of the modes.

Agbo and Zhang (2017) emphasize the results of synchromodality, comparing it with a fixed schedule model and a sequential model, where barge and rail schedules are optimized separately. Synchromodality offers cost savings of 22% compared with the fixed schedule model and of 8% compared with a sequential model. This cost reduction results from the decrease in road transportation and fewer waiting time penalties. The modal shift is optimized; 56% of barge transport and 27% of rail transport. The modal shift enhances sustainability. The paper does not discuss the decrease of emissions in numerical values. According to Agbo and Zhang (2017), synchromodality offers higher effectiveness and efficiency due to the flexible free mode booking, the better utilization of the modes, and the modal split. With free mode booking, the carrier has the freedom to choose the mode of transportation for an order since the customer does not specify the mode of transportation at the moment of booking the order.

Qu et al. (2019) stress the importance of synchromodality by comparing it to rigid planning, where barges departure with a fixed schedule and trains remain their flexible departure, and non-split shipment planning, which makes it impossible it split orders in contrary to the suggested model. The paper concludes that synchromodality is more flexible in service rescheduling, and has a better modal split.

Ambra et al. (2019) compare unimodal transport with intermodal transport, and intermodal transport with synchromodal transport. Intermodality leads to higher lead times, longer distances, and higher costs than unimodal freight transport. The extra handling cost accounts for the higher costs due to the modal shift. It is justified to have the extra handling cost for long distances, between 800 and 1200 km, because the lower cost per km for other than road transport balances this out. Synchromodality leads to more orders that are not only transported by road transport, i.e., from 26,5% in intermodality to 39,5%. The reason for the difference in the two concepts is that in a synchromodal network trucks more orders are sent to inland water-way terminals further away, while in an intermodal network they opt for the rail terminals. These shifted orders result in a better modal split. However, there are no significant differences in cost and distance. The lead-time even increases due to the choice of the model to opt for terminals that are further away from their route. This is because synchromodality is risk-averse; at smaller terminals further away, the probability of disturbances is lower. In an intermodal network, the containers wait when a disturbance occurs, while at synchromodality, the system urges to find other solutions. Those detours can be longer than waiting for the disturbance to stop. The third reason that the lead-times increase is the modal shift. With intermodality, rail transport is used more than inland waterways compared to the synchromodal model. Inland waterways transport has a limited speed, causing longer lead times.

Pérez Rivera and Mes (2019) compare their integrated model of drayage and long-haul operations with a non-integrated model, where drayage and long-haul operations are scheduled independently. The integrated model caused a cost reduction of between 4% and 24% in networks with a majority of pre-haulage freights. However, in some network characteristics, the difference between the two models is small. For example, in a network with a majority of end-haulage freights, the cost reduction is almost negligible.

Larsen et al. (2021b) applied a simulation experiment for the hinterland of Rotterdam. The researchers wanted to state their model for Secure Departure Learning. The results showed that Secure Departure Learning performs better than barge departures with a fixed schedule due to the better utilization of the vehicles. However, central planning of the barges and trucks yields better performance as a result of the higher degree of cooperation. Central planning refers to planning the barges departures and the truck routes simultaneously and together by one party. Larsen et al. (2020) came to a similar conclusion that Departure Learning outperforms a fixed schedule. Although, central planning is a better option. However, due to the withholding of information of the different parties, Departure Learning and Secure Departure Learning are good alternatives to utilize the capacity of the vehicles.

Yee et al. (2021) make a comparison between intermodality and synchromodality. Synchromodality reduces costs by 1.35% more than intermodality. Synchromodal transport slightly shortens the delivery time of shipments. The notable result from this numerical experiment is that in the synchromodal system, the emissions were higher than in the intermodal network. The higher emissions are caused by the increase in the use of trucks and barges in a synchromodal model compared with an intermodal network, that relies more on rail transport. Trains create lower emissions than barges and trucks. To solve the problem of the higher emissions, another objective function, targeting emissions, should be included in the model.

8. Conclusions and insights

The gap between the synchromodal planning models and the implementation in real life is huge. The planning models are still theoretical games that are never applied in real-life to assess their value, to show how realistic these models are, and to detect future research directions. This section gives an overview of the insights of this literature review.

Various decisions must be made at different planning levels, i.e., strategic, tactical, and operational. These decisions have different scopes. At the strategic level, infrastructure and investment decisions are taken. Yet, in literature, it is not defined who the decision-maker is. Whose responsibility is it to design the physical network? Are governments willing to invest in better infrastructure? These questions arise by reviewing the literature. The previous levels should be well developed to apply the synchromodal planning models on the operational level.

The various models reviewed in this paper use different methodologies, from pure mathematic models to heuristics. Most models stress the importance of real-time data. Yet, the papers do not specify how they will require this data. Which investments are necessary to handle real-time data? Is our current 4g network capable of handling all this information overflow in real-time?

The computing time of the models is a downside. Most researchers argue that the computing time is too long. Synchromodal transportation is all about making decisions in real-time. However, the real-time decisions seem impossible if the computing time takes too long.

Synchromodality considers only container transportation. However, container transportation is only a tiny part of freight transportation. In 2020 only 5.9% of the road transportation in Europe was container transport. Rail transportation of containers had a more significant share in 2020, i.e., 20.6% (Eurostat).

Only three of the reviewed models include multiple objective functions. All other models only try to optimize the costs. Before cost-saving, sustainability and societal factors, like noise and congestion, must be considered in the models due to the importance of tackling those problems. However, minimizing cost is essential to encourage companies to choose synchromodal transport service providers.

Only a few studies compare their methodology with other methodologies to assess their model. To know how reliable a model is, and to evaluate which model is closest to reality, and to know which research direction to take in the future, it is essential to compare different models with each other.

The empirical studies applied in the research are mainly hypothetical cases and not actual implementations of synchromodality. The hypothetical cases make the models more theoretical games than models ready to be implemented by companies.

Synchromodality is a promising change-maker. Nonetheless, there is a long way to go before synchromodality can be implemented in our daily life.

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